Analysis of charred Herculaneum papyri through pulsed thermography

by S. Ceccarelli*, Giovanni Caruso*, Loredana Luvidi*, Simona Boccuti*, Costanza Miliani*, Graziano Ranocchia**

* National Council of Research, Institute of Heritage Science (CNR-ISPC), Italy

** Department of Philology, Literature and Linguistics, University of Pisa, Italy

Abstract

This paper presents the latest results on the application of pulsed thermography to the analysis of fragile carbonised papyri from the ancient town of Herculaneum (Italy), aiming at improving text readability and characterising the papyrus substrate. Qualitative and semi-quantitative evaluations were carried out on the thermal data to understand the material behaviour and identify areas where inked parts are not clearly visible to the naked eye but are still detectable through the technique. The outcomes are promising for the legibility and the edition of the Greek philosophical works contained in these papyri and for a general knowledge of unrolled Herculaneum papyri.

1. Introduction

Non-invasiveness and portability are key factors in Heritage Science, especially in the case of analysis of extremely fragile items. This is particularly true for Herculaneum papyri, which represent one of the most extraordinary archaeological discoveries of all times, being the only library directly surviving from antiquity and providing insights into classical literature and philosophy [1]. These precious manuscripts survived the eruption of Mount Vesuvius in 79 AD thank to the thermal shock they underwent as a consequence of the volcanic surge that buried Herculaneum [2]. Since their discovery during the excavations in the mid-18th century, several attempts have been made to unroll the scrolls [3]. The carbonization process and subsequent unrolling procedures produced many unrolled pieces with a very complex morphology and a high level of difficulty in reading the texts. During the last few decades, several non-invasive techniques have been adopted with the aim of text detection and enhancement, such as near-infrared technical photography [4], shortwave-infrared hyperspectral imaging and high-resolution near-infrared digital microscopy [5]. Furthermore, partial virtual unrolling was carried out in order to decipher unopened papyri by using X-ray computed-tomography techniques [6,7]. Finally, important results about the layout of these Greek papyrus bookrolls were obtained with the application of macro-X-ray fluorescence imaging, which provided the first experimental proof of the use by ancient scribes of lead-drawn ruling lines for textual layout [8]. In this context, this paper presents a further development of an ongoing study for the analysis of Herculaneum papyri with the use of active thermography in the pulsed mode. This technique has proven efficient in detecting inked areas and mapping adhesion zones on the cardboard supports [9]. This non-destructive photo-thermal approach consists of recording the infrared (IR) radiation emitted by the sample after it is heated by the absorption of short pulses of visible (VIS) light emitted by flash lamps [10]. This method is useful for the detection of hidden details in layered structures such as paintings [11-12] or multi-part objects like bronze statues [13] or bookbinding [14-15]. Thus, this contribution shows the application of pulsed thermography (PT) for the analysis of charred papyri with the purpose of improving text legibility and characterising the papyrus substrate. Finally, qualitative and semi-quantitative analyses of the thermal data were conducted to evaluate the behaviour of the ink/papyrus materials and to identify areas where the inked parts are not clearly visible but can nevertheless be detected using this technique. The results are promising in terms of improving the legibility of the Greek philosophical works transmitted by unrolled Herculaneum papyri.

2. The Herculaneum papyri

The objects under investigation are sections of unrolled, charred papyrus stored in the “Officina dei Papiri” at the National Library of Naples "Vittorio Emanuele III". In particular, during the unrolling process carried out in the 19th century, the scrolls were cut into fragments which were then glued onto cardboard. Finally, all fragments are placed inside metallic frames (‘cornici’) and preserved in specially designed cabinets. Each fragment measures approximately 40 cm by 25 cm, and the papyrus sheet has an average thickness of around 0.15 mm. The text is written in vertical columns that are slightly inclined to the left with letters measuring approximately 3-4 mm.

Although the unrolling process enabled these important manuscripts to be opened and thus consulted directly, it also resulted in the formation of fragmented, multi-layered structures; this, combined with the very dark substrate due to carbonization, has made the objects difficult to decipher (Figure 1).

Figure 1. Herculaneum charred papyri: from the image, the complex morphology and readability difficulty are clearly visible.

3. The methodological approach

The fragments were analysed with the thermographic technique in the pulsed configuration. In addition to image processing, thermal signal analyses were carried out to study the differences in behaviour between the materials involved (ink and papyrus substrate).

3.1. Pulsed Thermography

The thermographic measurements were carried out by using a FLIR X6800sc infrared camera recording in the MWIR spectral range (3.5–5 µm, cooled FLIR InSb detector, 25 µm pitch, FPA 640 × 512 pixels, frame rate 520 Hz at the maximum spatial resolution, NETD < 20 mK at 30°C). When analyzing works of art, the amount of thermal energy delivered to the object should be minimized to mitigate the risk caused by an excessive rise in temperature or by excessive light absorption [16-17]. For this reason, this study used two flash lamps to produce sample heating, delivering 3 ms long pulses that induced an estimated temperature increase of less than 5 degrees on the surface. The camera was positioned perpendicularly with respect to the investigated papyrus, and the flashes were oriented at 45° to the papyrus surface (Figure 2). Furthermore, custom glass and water filters were fitted to the flash lamps to prevent infrared radiation from the heated lamps from reaching the papyrus surface and reflecting towards the camera. This would have had a negative effect on the contrast of the ink appearing in the thermograms.

Figure 2. PT setup *in situ* during the acquisition on papyri fragments.

As the text is written on the front surface of the papyrus, it is expected to appear with the maximum contrast in the very first thermograms after the flash pulse. Accordingly, the maximum frame rate of 520 Hz has been used to keep the spatial resolution of the camera at its maximum value, with 2 seconds-sequences recorded for each acquisition.

3.2. Thermal data analysis

A semi-quantitative analysis of the thermal signal was performed on the textual and papyrus substrates in order to understand how the two materials behave thermally. Furthermore, this examination provides information on the presence or absence of inked features where these are not clearly discernible. Additionally, the study of the heat dissipation has been carried out in correlation with the effect of the edge distortion of the letters [18].

4. Results

The images extrapolated from the thermographic sequences obtained using the PT method successfully revealed several textual portions in every fragment, even in cases where the text was almost illegible to the naked eye. This can be appreciated in Figure 3. Here, the text is clear and sharp and has been accurately detected by the PT.

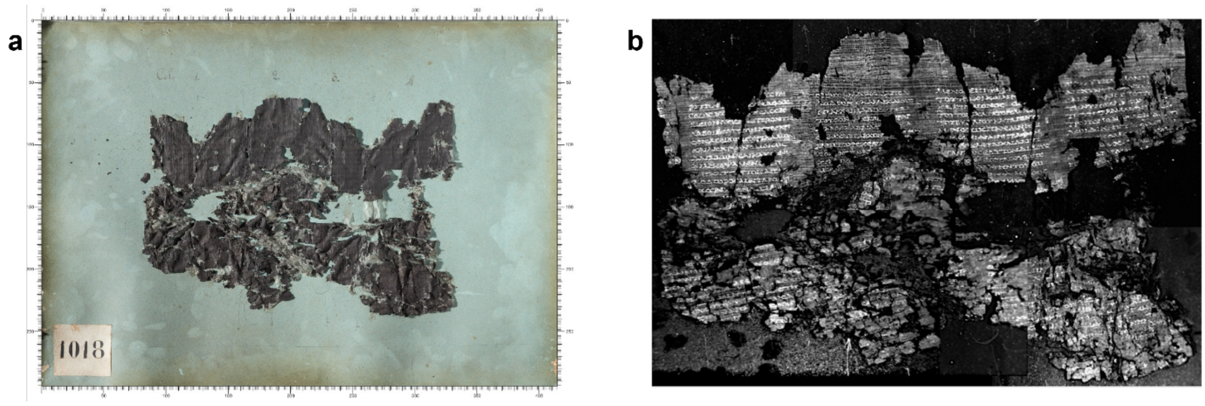

Figure 3. PT results: a) Visible image of *P.Herc*. 1018, 'cornice' 1; b) PT image acquired just after the flash pulse, where the textual contents are clearly discernible. (*adapted from Ceccarelli, S. et al. Pulsed thermographic analysis of Herculaneum papyri. Sci Rep 15, 34466 (2025). https://doi.org/10.1038/s41598-025-19911-w* https://creativecommons.org/licenses/by/4.0/)

Moreover, examining the PT sequence over a longer period, the pattern of the support can be appreciated (Figure 4b). In particular, the thermographic image shows the structure of the papyrus down to the single fibres.

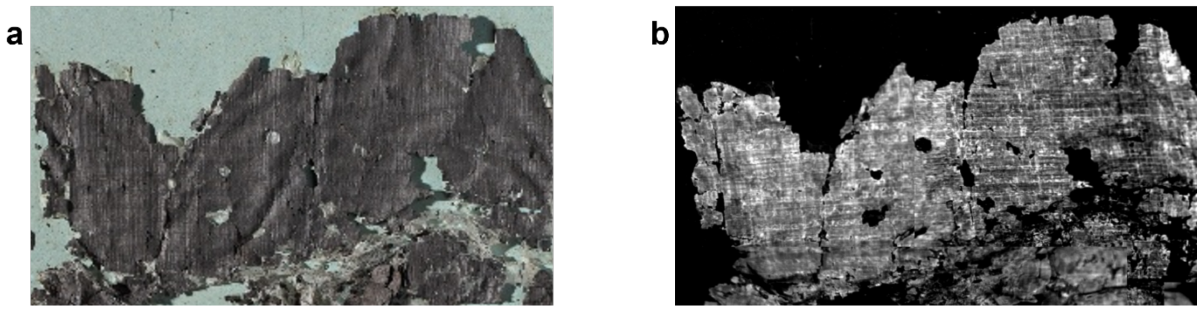

Figure 4. PT results: a) detail of visible image of *P.Herc*. 1018, 'cornice' 1; b) PT image acquired at larger times after the flash pulse, where the structure of the papyrus fibers can be noticed.

By analysing the behaviour of the thermal signals in correspondence with the text and papyrus substrate (red and green crosses in Figure 5b, respectively), differences in trends between the two features can be noticed (Figure 5c). In particular, the signal of textual parts (red line) indicates a greater increase in heating than that observed with papyrus, confirming the different thermal behaviour of the two materials. As a further investigation, an uncertain point was selected in an area where there should be text, but which is no longer visible, not even on the thermal image (blue cross in Figure 5b). Indeed, by visual inspection no letters are clearly visible, but the thermal trend of the selected point (blue line in Figure 5c) has a similar behaviour to ink, indicating a greater heating of the area compared with the substrate and thus a probable vanished letter.

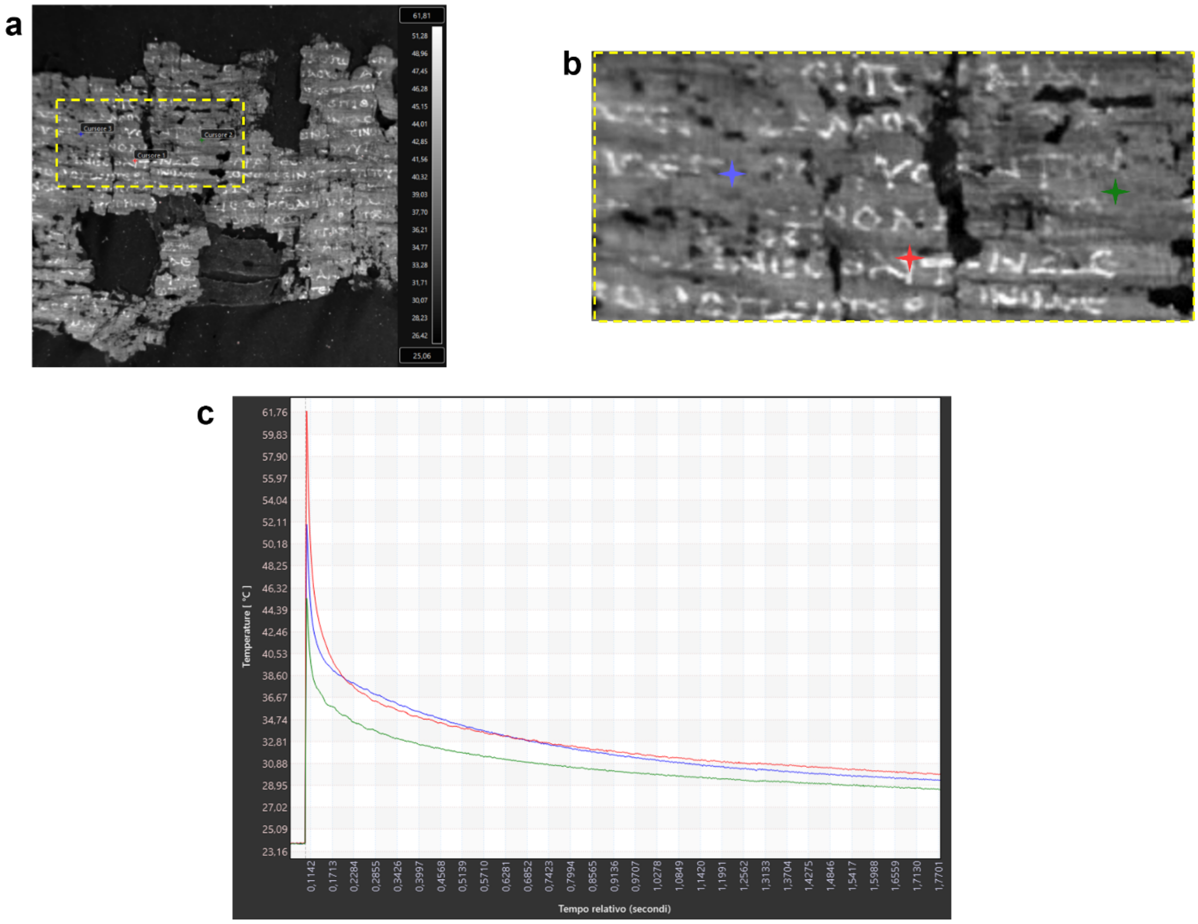

Figure 5. Thermal data analysis: a) investigated area; b) selected points where red is on the text, green on the papyrus substrate and blue is an uncertain point; c) thermal signals of the three points the different thermal behaviour of the two features is appreciable and the uncertain point can be associated to an inked element.

Finally, the analysis of edge distortion of textual elements allowed preliminary evaluations on the heating dissipation in these particular type of items. In Figure 6, the thermal signal profiles over the ink edges corresponding to the thermal images are reported.

The analysis shows increasing contrast in the first thermograms of the sequence (blue and red lines), where edge distortion is minimal, and the text is therefore clearly legible. As the time delay increases, the heat dissipates, and the contrast decreases (yellow line), providing a blurred image caused by lateral heat conduction.

This provides semi-quantitative information on the ‘depth’ of the text: in superficial texts, such as in the case of Herculaneum papyri, the profile is not flattened, and the blurring is minimal, resulting in a good legibility level. In buried texts, the signal is weaker because it takes longer to reach the sensor, resulting in greater blurring and therefore a loss of legibility [18].

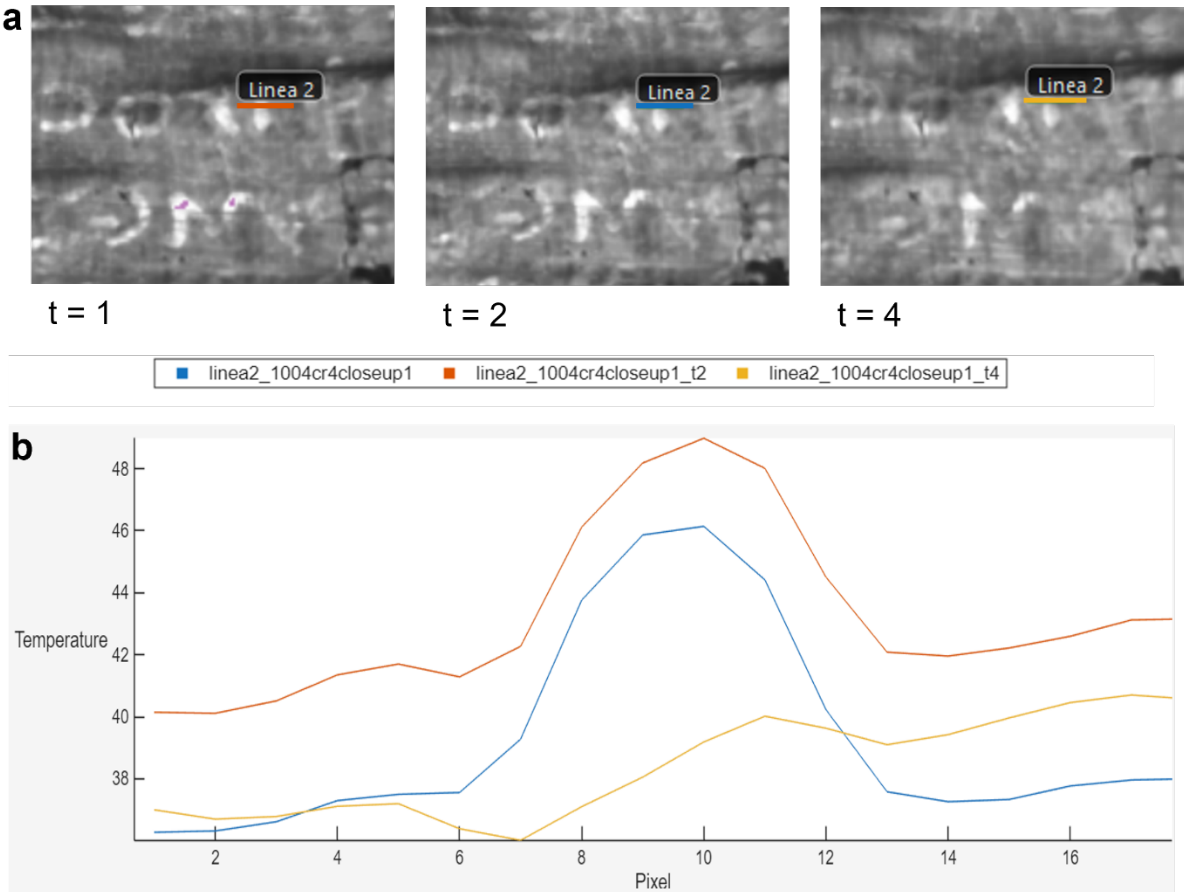

Figure 5. Edge distortion analysis: a) thermal images of the investigated papyrus recorded at increasing delay times; b) thermal signal profiles in correspondence of an inked letter as indicated in a).

5. Conclusions

The paper presents the latest results of an ongoing work by using a thermographic approach on the precious Herculaneum papyri, which have survived - albeit in a precarious state - thanks to their carbonization following the famous eruption of Mount Vesuvius in 79 AD. The critical condition of the manuscripts and the unrolling processes that they have been undergoing over the centuries have resulted in complex artefacts that represent both scientific and philological challenges. This study aims to improve the ability to read the unrolled fragments by analysing the thermal behaviour of the materials through the application of pulsed thermography. This technique has produced promising results in terms of enhancing textual legibility, even in the case of a very dark substrate. Furthermore, qualitative and semi-quantitative data analysis provided a new tool for understanding the materials and their thermal behaviour.

Reference

[1] Sider, D. The library of the Villa dei Papiri at Herculaneum (Los Angeles, 2005).

[2] Scandone, R., Giacomelli, L., and Rosi, M.: Death, Survival and Damage during the 79 AD Eruption of Vesuvius which destroyed Pompeii and Herculaneum, J. Res. Didact. Geogr., 2, 5–30, https://doi.org/10.4458/2801-01, 2019.

[3] Angeli, A. Lo svolgimento dei papiri carbonizzati. Papyrologica Lupiensia 3, 43–84 (1994).

[4] Pavone D. P., Caliri C., Romano F. P., Miliani C., Ranocchia G., (2022). Studio e sviluppo di tecniche fotografiche per la documentazione, conservazione e lo studio della collezione dei papiri carbonizzati di Ercolano nel contesto del progetto GreekSchools. Plenary project meeting. https://doi.org/10.5281/zenodo.8284756.

[5] Ceccarelli S., Pavone D. P., Gasperini I., Serra I. A., Ranocchia G., and Miliani C., "Infrared imaging techniques for the readability enhancement of Herculaneum papyri: a comparison between technical photography and high-resolution digital microscopy", Proc. SPIE 13569, Optics for Arts, Architecture, and Archaeology (O3A) X, 135690M; https://doi.org/10.1117/12.3066663.

[6] Bukreeva, I. et al. Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography. Sci. Rep. 6, 27227 (2016).

[7] Seales, W.B. et al, From damage to discovery via virtual unwrapping: Reading the scroll from En-Gedi.Sci. Adv.2,e1601247(2016).DOI:10.1126/sciadv.1601247.

[8] Romano, F.P.,et al., Layout of ancient Greek papyri through lead-drawn ruling lines revealed by Macro X-Ray Fluorescence Imaging. Sci Rep 13, (2023). doi:10.1038/s41598-023-33242-8.

[9] Ceccarelli, S., Rippa, M., Caruso, G. et al. Pulsed thermographic analysis of Herculaneum papyri. Sci Rep 15, 34466 (2025). https://doi.org/10.1038/s41598-025-19911-w.

[10] Maldague, X.P.V. Introduction to NDT by active infrared thermography, Mater. Eval. 60 (2002) 1060–1073.

[11] Mercuri F., Ceccarelli S., Orazi N., Cicero C., Paoloni S., Felici A.C., Matera F., Nuzzo., Zammit U., Combined use of infrared imaging techniques for the study of underlying features in the Santa Maria in Cosmedin altarpiece, Archaeometry, 2021, https://doi.org/10.1111/arcm.12653.

[12] Rippa, M., Vigorito, M. R., Russo, M. R., Mormile, P., Trojsi, G. Active Thermography for Non-invasive Inspection of Wall Painting: Novel Approach Based on Thermal Recovery Maps, J. Nondestruct. Eval. 42 (63) (2023).

[13] Luvidi L., Casanova Municchia A., Konstantakopoulou E., Orazi N., Ferretti M., Caruso G., Combined Use of Non-Destructive Analysis Techniques to Investigate Ancient Bronze Statues. Sensors 2025, 25, 1727. https://doi.org/10.3390/s25061727.

[14] Sfarra, S. et al. D. A multi-technique non destructive approach for characterizing the state of conservation of ancient bookbindings. J. Therm. Anal. Calorim. 2018, 132, 1367–1387.

[15] Orazi N., Mid-wave Infrared Reflectography and Thermography for the Study of Ancient Books: A Review. Studies in Conservation, 65(8), 437–449. https://doi.org/10.1080/00393630.2020.1734383.

[16] Dritsa, V.; Orazi, N.; Yao, Y.; Paoloni, S.; Koui, M.; Sfarra, S. Thermographic Imaging in Cultural Heritage: A Short Review. Sensors 2022, 22, 9076. https://doi.org/ 10.3390/s22239076.

[17] Yoon S.T., Park J.C., Cho Y.J. (2022) An experimental study on the evaluation of temperature uniformity on the surface of a blackbody using infrared cameras, Quantitative InfraRed Thermography Journal, 19:3, 172-186, DOI:10.1080/17686733.2021.1877918.

[18] Ceccarelli S., Caruso G., Mercuri F., Paoloni S., Zammit U., Orazi N., Study of the edge distortion effect in thermographic detection in semi-transparent Cultural Heritage, Proc. of IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage, 2021.